Project IST-2001-33520 CC
(Control and Computation)
Second Year Deliverables

January 2004

1 D-MG-2: Management

The project finished its second year. The cost statement for the first year has been approved and the payments have been transferred to the partners. Two plenary project meetings took place:

	Dates	Place	Participants
1	16-17.6	Amsterdam	20
2	22-24.9	Siena	19

The next project meeting is planned for January in Rome, co-located with the review. In addition to these meetings collaboration between partners is handled via e-mail and mutual visits summarized in the following table:

Visitor	From	To	Dates
A. Bemporad	Siena	ETH	22-26.3
N. Giorgetti	Siena	ABB	1-6.12
J. van Schuppen	CWI	Parades	27-31.1
J. van Schuppen	CWI	Parades	24-28.3
J. van Schuppen	CWI	Parades	20-24.10
A. Balluchi	Parades	CWI	18-19.6
O. Maler	Grenoble	CWI	18.6
M. Larsson	ABB	ETH	22.1
M. Larsson	ABB	ETH	10.9
M. Larsson	ABB	ETH	26.11
M. Larsson	ABB	Lund	12.5
M. Larsson	ABB	Grenoble	1.12
F. Torrisi	ETH	Siena	11-17.11

As this table demonstrates, the collaboration between the partners around the case-studies has increased significantly. The automotive case-studies are currently treated by Parades, Grenoble and CWI while the ABB case-study is treated by ETH, Siena, Lund and Grenoble.

On the other hand the case-studies by the EDF failed to attract the attention of most partners. This was not due to their lack of interest — on the contrary, the problem they posed are very typical hybrid problems. However, due to confidentiality constraints, the access to the real models was very limited which could make the treatment of this case study more like an exercise in piecewise-affine system rather than a work on the case-studies. Consequently, after the conclusion of the report on PP1 (Water level problem) and the presentation of PP2 (Fossil power plant) it was decided to stop working on these case-studies and divert 60K Euro, originally intended for this purpose, toward other activities, including dissemination and work on the other case-studies.

2 D-CH-2: Control of Hybrid Systems

In this second year of the project we see a clear shift in the focus of the activities that are part of this work package. Work on the system theoretic fundamentals that are essential prerequisites for control, like system identification, model reduction and observability has continued. Controller synthesis has, however, become the area of main activity and has progressed to a point that tools for solving practical problems are emerging. In collaboration with several industrial partners a wide range of applications has been tackled by the different groups. Also, some of the tools have matured to a point that the integration of the various contributions into a software toolbox has been initiated.

As a consequence of the application work it has been recognized that, regardless of the significant progress in the available design tools and the increase in computer power, *exact* "optimal" controllers are only feasible for relatively small systems and that alternative suboptimal techniques are essential to design controllers for larger hybrid systems. Various new computation schemes and structural decomposition scheme have been proposed to deal with these challenges, which are likely going to receive even more attention in the third year.

2.1 Modeling, Model Reduction, and Identification

2.1.1 Identification of hybrid systems for controller synthesis

We investigated techniques for generating piecewise affine hybrid dynamic models from input/output experimental data or from known nonlinear models, with the goal of obtaining models that are suitable for the synthesis of hybrid controllers. In [BGPV03a, BGPV03b] we developed an identification algorithm based on greedy randomized techniques and linear and quadratic programming, that have an excellent performance both in terms of CPU time and quality of the identified model. In [RBL04] we developed an alternative technique based on mixed-integer programming that is computationally less efficient, although it globally minimizes the data fit criterion.

2.1.2 Models of hybrid systems for controller synthesis

We theoretically investigated and developed tools for modeling hybrid systems in a way that is tailored to controller synthesis. In [Bem03a] we proposed algorithms for translating discrete hybrid automata (DHA) modeled with the tool HYSDEL and mixed logical dynamical (MLD) systems into an equivalent piecewise affine (PWA) form. In [BG03, BG04] we proposed to model DHA as a collection of mixed-integer equality/inequality constraints and Boolean constraints, so that hybrid optimal control problems can be solved using "hybrid" solvers that combine mixed-integer programming (MIP) and constraint programming (CP) techniques.

2.1.3 Efficient Mode Enumeration of Compositional Hybrid Systems

A hyperplane arrangement is a polyhedral cell complex where the relative position of each cell of the arrangement and the composing hyperplanes are summarized by a sign vector computable in polynomial time. This tool from computational geometry enables the development of a fast and efficient algorithm to translate the composition of hybrid systems into a piecewise affine model and to determine if the composition is well-posed. In particular, hybrid systems modeled in HYSDEL [TBM00] can be transformed into an equivalent piecewise affine representation. The tool [GTM03a] provides also information on the real combinatorial degree of the system which can be used to reduce the size of the search tree and the computation time of the optimization algorithms underlying optimal and model predictive control. Examples are presented illustrating the algorithm and showing its computational effectiveness. The MATLAB code is available upon request.

2.1.4 Optimal Complexity Reduction of Piecewise Affine Models Based on Hyperplane Arrangements

Given a piecewise affine (PWA) model, it is shown how to derive an *equivalent* PWA model that is *minimal* in the number of regions [GTM03b]. The algorithm is based on the cells of the hyperplane arrangement which are already given, when the PWA model is the result of the mode enumeration algorithm [GTM03a]. In particular, the algorithm executes a branch and bound on the markings of the cells of the hyperplane arrangement assuring optimality. As we refrain from solving additional LPs, the algorithm is not only optimal but also computationally feasible. The applicability of the algorithm can be extended to derive minimal PWA representations of general PWA models by first computing the hyperplane arrangement. Examples illustrate the algorithm and show its computational effectiveness. The results are summarized in [GTM03b].

2.2 State Estimation

2.2.1 Observer design for hybrid systems

Observability for hybrid systems has been further investigated. In [BBDSV03], we introduced the notion of generic final–state asymptotically determinable hybrid systems and gave sufficient conditions for a linear hybrid system to be generic final–state asymptotically determinable. These conditions show that generic final–state asymptotic determinability can be verified in some cases even if each of the continuous subsystems of the hybrid system is not observable. More precisely, these conditions are related to the minimum and maximum sojourn time in each location as well as on the dimension and orientation of the unobservable subspaces and on the reset mappings between them. This result is based on the synergy that can be exploited between the interacting continuous and discrete behaviors exhibited by hybrid systems. A scheme for a hybrid observer that identifies the current location of the hybrid system after a finite number of steps and converges exponentially to the continuous state has been proposed.

2.2.2 Oberservability

The concept of observability of piecewise-affine hybrid was studied by Collins and van Schuppen [CvS04], motivated by some dissatisfaction with certain presentations on the topic on Hybrid Systems workshop of 2003. The main results obtained are an equivalent condition for observability and a sufficient condition for observability. A consequence of the results is that the general problem of observability is intractable. The best what can be obtained are sufficient conditions for observability for engineering motivated subclasses of hybrid systems. It is still uncertain as to whether the problem of observability for this particular subclass of hybrid systems is undecidable. Sontag (1995) claims that the observability problem for piecewise-linear systems is undecidable.

2.3 Optimal Control Computation

2.3.1 Constrained Finite and Infinite Time Optimal Control of Piecewise Affine Systems

We theoretically investigated a modification of the algorithm described in [BBBM03c, BBBM03b, Bor02] for computing the solution to the constrained finite time optimal control (CFTOC) problem for discrete-time linear hybrid systems [BCM03a, BCM03b]. As opposed to the quadratic performance index used in the original algorithm we used a linear performance index. The algorithm combines a dynamic programming strategy with a multi-parametric linear programming solver. By comparison with literature results it was shown that the algorithm presented solves the considered class of problems in a computationally efficient way.

We extended the idea of the aforementioned algorithm of the CFTOC problem in order to solve the constrained infinite time optimal control (CITOC) problem for the class of discrete-time linear hybrid systems. When a linear performance index is used the infinite time optimal solution is a time-invariant piecewise affine (PWA) state feedback control law. We presented an algorithm that computes the optimal solution in a computationally efficient manner. The algorithm also combines a dynamic programming exploration strategy with a multi-parametric linear programming solver and basic polyhedral manipulation. Several examples of different order were computed with both algorithms to show their efficiency.

2.3.2 Synthesis of optimal controllers

For continuous-time autonomous affine systems, in [BCGS03, SCGB03] we proposed two alternative techniques for synthesizing the optimal modes and switching times that minimize an infinite-horizon quadratic control problem.

In [BG03] we proposed the use of constraint programming (CP) and mixed-integer programming for efficiently solving hybrid optimal control problems. The technique was extended in [BG04], where we proposed an optimal control algorithm that makes use of very efficient SAT solvers for satisfiability of Boolean formulas and convex programming for optimization of performance. The technique is currently investigated on a complex industrial scheduling problem, and it is already apparent that traditional pure MIP approaches are outperformed by the new "hybrid" solvers.

Control problems where the main hybrid nature stems from the quantization of the input signals were addressed in [PPBB02], and a general multiparametric nonlinear integer programming technique was developed in [Bem03b] for obtaining piecewise constant solutions to quantized optimal control problems.

A more direct approach to computation of the optimal cost was taken in the thesis work by Sven Hedlund [HR02, Hed03]. An inequality version of the classical Hamilton-Jacobi-Bellman was stated for hybrid systems and solved using linear programming and state space gridding. The method is restricted to small state dimensions but is otherwise very general and has strong theoretical support [RH03].

2.3.3 Control problems with safety specifications

The problem of synthesizing controllers for hybrid systems subject to safety (state-invariance) specifications has been considered. In this class of control problems, the controller goal is to keep the state of the closed-loop system within a specified set of good states, while the environment tries to force the system outside the good set. In [BBV+03a] and [BBV+03b] we studied hybrid systems with lower bounds on the separation between occurrence times of consecutive discrete moves. These systems arise when modeling minimal delay times between events, either in the controller, or in the environment. For such systems, we provided techniques for solving differential games in reduced state spaces. This step is the key difficulty in carrying out the synthesis procedure for hybrid safety specifications. The main idea is to discretize information about whether discrete moves are enabled or not. We demonstrate our technique by successfully synthesizing the maximal set of controllers for a hybrid model of a heating system with discrete controls and disturbances, and continuous controls and disturbances.

2.3.4 Strong Variations Algorithm for Switched Hybrid Nonlinear Systems

This work [AA] focuses on the gain in efficiency that may be obtained when using strong variations-like algorithms to solve optimal control problems for switched hybrid nonlinear systems. After a review of existing algorithms, a simple version of a strong variations algorithm is proposed together with some new convergence results. The key features in the proposed algorithm are (i) the absence of a priori assumptions on the number of switches, (ii) the absence of complexity explosion with the state dimension, and (iii) the use of a unified approach for both the continuous and the discrete inputs.

The algorithm has been applied to several examples to demonstrate its efficiency. These examples include an induction machine with an eight-dimensional state vector, where the control goal was to optimally attenuate the harmonics of given frequencies, as well as known examples from the nonlinear hybrid systems control literature. The preliminary results indicate impressively short computation times (even with relatively ”bad” initial guesses). Thus the algorithm may be applicable to problems of meaningful size.

The potential use of a modified version of the strong variations algorithm for solving optimal control problems for nonlinear hybrid systems has been first pointed out in the note [AA03].

2.4 Controller Complexity Reduction

2.4.1 Low Complexity Controller Synthesis via Multi-Parametric Programming

Last year, several advances have been made in the field of obtaining controllers of low complexity for constrained linear and PWA systems. The focus has been on obtaining low complexity feedback controllers by employing multi-parametric programming techniques [BMDP02]. Although the associated computations are performed off-line, the inherent computational complexity soon becomes intractable even for medium sized problems. The focus of our research has therefore been threefold:

First, improved computation and algorithmic schemes were developed which compute the feedback controllers faster and more efficiently. This issue is tackled by combining reachability analysis with multi-parametric programming as presented in [GBTM03]. Second, suboptimal control strategies were implemented in order to obtain simple control laws. Specifically minimum-time, and one-step Model Predictive Controllers with robust stability and constraint satisfaction guarantees were designed in [GPM03, GM03] based on multi-parametric programming. In [GWKM03], complexity reduction was achieved by applying triangulation techniques to control invariant sets. Third, various post-processing algorithms were developed which serve to reduce the controller complexity a posteriori and help to obtain strong properties of the closed loop system. Specifically, interpolation may be used to reduce the number of controller regions [RG03] and LMIs in combination with invariant set computation for piece-wise affine systems can serve to yield strong stability properties for the closed-loop system [GLPM03].

Multiparametric quadratic programming techniques were studied in [TJB03a, TJB03c] for the synthesis of piecewise affine optimal controllers for linear systems with constraints and quadratic cost functions. Based on a dynamic programming perspective, similar techniques were investigated in [dlPnABC03]. Suboptimal techniques were developed in [BF03b] for reducing the complexity of the solution, and extended to the general class of nonlinear convex multiparametric problems in [BF03a]. Multiparametric QP was also employed in [BTZ03] for the synthesis of almost $\mathcal{L}_2$-optimal anti-windup schemes. For uncertain linear systems subject to constraints, dynamic programming and multiparametric linear programming was proposed in [BBM03b] for obtaining robust piecewise affine optimal controllers. Optimal control of uncertain hybrid dynamical systems was instead dealt with in [SBBdC03], where an ad-hoc branch & bound algorithm was proposed. Algorithmic aspects for the implementation of piecewise affine controllers were investigated in [TJB03b] and in [BBBM03c, BBBM03a].

2.4.2 Low Complexity Controller Synthesis via Dynamic Programming Relaxation

In this area, the PhD student Bo Lincoln was active already before the project, so we could pursue the project objectives at full speed from the the very first day. The first journal publication in the area [LB02] was mainly based on activities before the start of the project. This paper considers off-line optimization of a switching sequence for a given finite set of linear control systems, together with joint optimization of control laws. A linear quadratic full information criterion is optimized and dynamic programming is used to find an optimal switching sequence and control law. The main result is a method for efficient pruning of the search tree to avoid combinatoric explosion. A method to prove optimality of a candidate sequence and corresponding control laws is presented.

The methods were considerably refined in conference papers during 2002 and 2003 [LR02, LR03a]. The papers present a general method for relaxation of Dynamic Programming. The method makes it possible to find suboptimal solutions with known error bounds to hard problems. The bounds are chosen by the user, who can then effectively trade-off between solution time and accuracy. Several examples from different domains where the method is highly useful are presented. This includes optimal switching between linear systems, with application to CPU scheduling as well as design of a DC/DC voltage converter. Other examples are control of piecewise linear systems, and Partially Observable Markov Decision Processes (POMDPs). The results are collected in the PhD thesis [Lin03] and a journal paper has been accepted for publication [LR03b].

2.4.3 Stabilization of linear discrete–time hybrid automata

A novel approach to the stabilization of linear discrete–time hybrid automata has been developed by Parades. The proposed synthesis methodology was obtained by extending to hybrid systems stabilization techniques based on the stable convex combinations method, originally developed for switching systems (see [ZBSVB03]). The key idea is exploiting the underlying automaton structure by restricting the control actions to the ones corresponding to cycles in the automaton, which are identified using regular language tools. Since the number of candidate control actions may be high, we obtained sufficient conditions for the elimination of several paths that are dominated by others, based on which an exploration algorithm has been proposed. The method was tested on an industrial problem in automotive engine control that motivated this research.

2.4.4 Control Synthesis for modular Discrete-Event Systems

Control synthesis for modular discrete-event systems was investigated in [KvS04]. The motivation of the investigation is modular control of hybrid systems in which a large hybrid system is the composition of many small such systems. Distinction of the hybrid systems into a discrete-event level and a continuous-space level then leads to control problems for modular discrete-event systems. The main problem for modular control is whether a control synthesis for each module separately followed by a composition of all local controllers, achieves the same control objectives as a centrally synthesized controller.

A theorem was formulated with a sufficient condition for the composition of modularly synthesized controllers to achieve jointly the same optimal solution as the centrally synthesized controller. The condition involves the concept of mutual controllability introduced by Sang-Heon Lee and Kai Wong. This covers the case of complete observations. In the case of partially observed modular discrete-event systems corresponding results were obtained which are phrased in terms of the concept of mutual observability.

2.4.5 Complexity of a Decentralized Control Problem for Discrete-Event Systems

The complexity of a decentralized control problem for discrete-event systems has been investigated in [RvS04]. The motivation of this work was the distributed control of hybrid systems. The sensor selection problem was primarily investigated. When designing a control system, the control engineer may have some discretion to choose which sensors the controller may use. For reasons of cost or simplicity, the designer may want to use as few sensors as possible in the system. Investigations of this problem were made at the level of centralized control for the discrete-event system because many of fundamental problem difficulties are not due to the continuous state or distributed nature of the distributed hybrid systems, but to the inherent difficulty of this optimization problem. It was shown that the computational issues associated with the sensor selection problem are directly related to a simple kind of graph problem which we call an edge-coloured directed graph ST-cut problem. Both these problems are NP-complete, but more surprisingly, it is computationally difficult to find approximate solutions. A number of heuristic polynomial time algorithms for computing approximate solutions to both the sensor selection and graph cutting problem were developed. The consequences for control of discrete-event systems are being worked out.

2.5 Performance Analysis

The first paper [LC02] in this area describes Jitterbug, a Matlab-based toolbox for real-time control performance analysis. The control system is described using a number of connected continuous-time and discrete-time linear systems. The control performance is measured by a continuous-time quadratic cost function. A stochastic execution model is used to describe when the different discrete-time systems are updated during the control period. Building different system models, the tool makes it easy to investigate how control performance is affected by e.g. input-output delay, sampling jitter, output jitter, lost samples, period overruns, aborted computations, and jitter compensation.

The second paper [SR02] is devoted to performance analysis of the servo problem for a wide class of nonlinear systems, including piecewise linear systems. A quantitative bound on system trajectories is derived. For piecewise linear systems the bound is shown to be computable in terms of linear matrix inequalities. A computational example is successfully completed.

2.6 Applications

The hybrid techniques developed by the consortium were applied to a variety of real problems.

2.6.1 Electronic Throttle Control

In automotive applications an electronic throttle is used to control the inflow of air to the vehicle engine. The electronic throttle is essentially a DC servo system, where the motor shaft rotation is transmitted through a gearbox to the shaft with the throttle plate. Movement of the plate continues until the motor torque is balanced by the torque generated by the return spring which is attached to the plate's shaft. Two nonlinearities in the throttle body make the control of the plate position a challenging task. One is friction in the gearbox transmission mechanism, and another one is the so called Limp-Home (LH) position nonlinearity that is a consequence of an embedded mechanical safety feature which guarantees a specific level of air inflow even in the case of total power failure.

We model the electronic throttle as a discrete time Piecewise Affine (PWA) system and design a Receding Horizon controller by solving a Constrained Finite Time Optimal Control (CFTOC) problem via Dynamic Programming (for more details see [BBBM03c] and [BVMP03]).

The solution – a PWA state-feedback control law – was tested experimentally with a sampling time of 5 ms. Experiments were carried out with a Pentium III 1.7 GHz machine running MATLAB 5.3 and using Real-Time Workshop with an A/D–D/A card as a computer-process interface.

2.6.2 Multi-Object Adaptive Cruise Control

Cruise control is a common and well known automotive driver assistance system in which the driver sets a reference speed and the engine is controlled so that this reference speed is maintained regardless of external loads such as wind, road slope or changing vehicle parameters. Adaptive Cruise Control (ACC) additionally takes into account the traffic in front of the car. In a multi-object adaptive cruise control problem the optimal acceleration of the driver's car is to be found respecting traffic rules, safety distances and driver intentions [MBM03]. The control objectives are

- to track the reference speed
- to respect safety distance if a neighboring car is in the same lane, and
- not to overtake on the right side of a neighboring car

while constraining acceleration and changes in acceleration and in deceleration. Loosely speaking we would like to maintain a comfortable drive for our car and respect traffic rules. The hybrid nature of the problem arises from the multiple objectives which include switches.

The optimal state-feedback control law (for a quadratic objective function) is found by solving the underlying Constrained Finite Time Optimal Control problem via Dynamic Programming [BBBM03c]. The optimal state-feedback control law was tested on a research car Mercedes E430. Special interfaces to throttle and brakes, sensor fusion, visualization and the ACC controller were running in a real-time environment with an 80 ms cycle time on an Intel Pentium4 1.4GHz machine with 500 MByte RAM.

2.6.3 Direct Torque Control (DTC)

In this project, hybrid control systems methodologies were applied to the Direct Torque Control (DTC) of 3-phase induction motors. The example studied is ABB's ACS6000 DTC drive, that uses a 1.5MW, 3.3kV induction motor and a 3.4kV three-level GTO inverter. The drive is modeled in the Mixed Logic Dynamic (MLD) [BM99] framework. Non-linearities are approximated through PWA functions and the switching state of the inverter is described using discrete variables. For control purposes, the control objectives are expressed in a cost function and an optimal control problem is formulated over a receding horizon. Through the solution of a Mixed-Integer Linear Program (MILP), the optimal control move is then derived as a combination of the discrete manipulated variables. The performance of the Optimal DTC scheme was evaluated through simulations that were carried out using ABB's simulink model of the ACS6000 drive. The look-up table ABB is currently using for the DTC core was replaced by the on-line optimization. The results obtained showed a significant improvement in the system's behavior, while the proposed methodology can incorporate and satisfy various and contradicting control objectives allowing for systematic controller design. It is also a promising tool for the design of control systems for more complicated drives, using multi-level inverters. The open questions currently investigated are the calculation of the explicit control law, that will allow the experimental verification of the Optimal Direct Torque Control scheme.

2.6.4 DC-DC Converters

Switch-mode DC-DC converters are power electronic circuits that are used in a large variety of applications. Their analysis and design both in the open and the closed loop have attracted wide research interest, and the quest for efficient control techniques is of interest for both the research and the industrial community. In this project a new solution approach to the optimal control problem of fixed frequency switch-mode DC-DC converters using hybrid systems methodologies was presented. In particular, the notion of the N-step model is introduced to capture the hybrid nature of these systems, and an optimal control problem is formulated and solved online using Model Predictive Control, which allows one to easily incorporate safety constraints such as current limiting in the controller design. A synchronous step-down DC-DC converter is used as an illustrative example. The converter is modeled as a hybrid system using the Mixed Logic Dynamic (MLD) [BM99] framework. This leads to a model that is valid for the whole operating regime and captures the evolution of the state variables within the period. Based on the MLD model, a Model Predictive Control (MPC) problem [Mac02] is formulated and solved. This allows for a systematic controller design that achieves the objective of regulating the output voltage to the reference despite input voltage and output load variations while satisfying the constraints. Simulation results were obtained, showing a closed-loop system with very favorable dynamical properties that demonstrate the prospects of this approach.

2.6.5 Various other hybrid control applications

Other application that were treated include: (*i*) supervisory control of an automotive robotized gearbox for reducing consumptions and emissions [BBM03a] (in collaboration with Fiat Research Center, Orbassano (TO), Italy); (*ii*) hybrid optimal control of a multi-product batch plant [PBT$^+$04]; (*iii*) hybrid optimal control of an asphalt base process [PBT$^+$03].

3 D-RM-2: Reachability-based Methods

This work-package is centered around the adaptation of verification and synthesis techniques originating in computer science to continuous and hybrid systems. The main progress in this research direction is summarized below:

3.1 Abstraction and model reduction

We have been continuing our work on predicate abstraction of hybrid systems. This technique has been recently shown to enhance the effectiveness of the reachability computation techniques; however, its success depends on the choice of the predicates used for abstraction. We therefore focused on the problem of analyzing counter-examples generated by the search in the abstract state-space in order to automatically identify new predicates which guarantee to rule out closely related spurious counter-examples in the refined abstract state space. Since in our approach reachable sets are represented by polyhedra, to solve this problem, we developed a method for finding hyperplanes that separate two sets of polyhedra. We implemented this counter-example guided abstraction refinement technique and experimented it on several case studies in automotive control. This work was published in [ADI03] and a journal version will appear in [ADI04].

Meanwhile a new technique for abstraction by projection has been developed in [AD03]. The main idea is to over-approximate a system of nonlinear differential equations by a hybrid system with differential inclusions in lower dimension. The approximation procedure uses ideas from qualitative simulation and a method for error control was developed. While this abstraction approach can be used for dimension reduction, its effective applications require the ability to deal with nonlinear differential inclusions. We developed a reachability analysis method for uncertain bilinear systems which, in combination with the abstraction by projection, allows to treat multi-affine systems. An experimental implementation of this technique enabled us to study a bacteria model in bioregulator networks.

In [BBV+03a] we study a special case of reduction of the continuous state space in the reachability procedure by partially hiding a continuous timer. A more complete abstract can be found in D-CH-2.

Another abstraction technique was developed in [SBM] in order to find maximal stabilization time for acyclic digital circuits composed of gates with bi-bounded inertial delays. Typically such systems can be modeled as timed automata with one continuous variable (clock) per gate and this renders the analysis of circuits with more than 10 gates intractable. The abstraction technique is based on decomposing the circuit into smaller sub-circuits and automatically approximating the sub-circuit in a conservative manner into a small timed automaton with one clock, that can be plugged as an input model for the rest of the circuit. Using this technique it was possible to analyze circuits with almost 100 gates.

3.2 Differential algebraic equations

This problem is motivated by the verification of analog and mixed-signal circuits since differential algebraic equations are often used to model circuit behaviors. We studied a technique for analyzing such equations which can be viewed as an extension of the projection methods from geometric integration to sets of trajectories. In addition, for efficiency purposes, this technique is combined with a 'hybridization' technique which approximates nonlinear characteristics by piecewise linear ones. The approach has been tested on several examples of analog circuits (such as a biquad low pass filter and a tunnel diode, [DDM04]). To extend this idea to mixed-signal circuits, we intend to work on an automatic generation of hybrid automaton models from commonly-used circuit specifications (such as VHDL-AMS).

3.3 Search-based methods

The idea of applying systematic simulation with a discretized input space as an alternative to standard hybrid verification techniques was suggested in the first year in [KMSK]. This year it has been has been further explored in [Ali03] for the purpose of synthesizing controllers. The idea is to find an open-loop control signal by discretizing the space of input signals (both in time and space) and searching for a sequence that will steer the system toward a target goal while respecting safety constraints using best-first search. A prototype implementation in Matlab has been developed and applied successfully to a toy problem of guiding a missile inside a tunnel. We are currently working on combining this approach with more traditional approaches for computing optimal controls.

3.4 Ellipsoids

In [CBB$^+$03] we described a new algorithm for reachability analysis that yields a tighter approximation than Botchkarev's algorithm, from which it derives. The new algorithm avoids the approximations caused by the union operation, and so it can prove that a region is unreachable by a given hybrid automaton, also when Botchkarev's algorithm returns otherwise, due to the over-approximations of the union operation (declaring reachable states which are not). Moreover, we introduced the notions of ϵ_H-*expansive automaton*, *approximation index of a calculus method* and $(\mathcal{C}, \delta)$-*compatibility*, to characterize a class of hybrid automata for which termination of the two algorithms can be proved. We also defined the *algorithmic approximation index* to measure the quality of reachability analysis algorithms, showing that the new algorithm has a better index than the original one.

3.5 Affine systems on polytopes

A complete characterization has been obtained of the domains of attraction of exit sets of affine systems on polytopes in the plane [HvS04b]. The problem is of interest to the understanding of the complexity of control problems for hybrid systems. It has been proven by Eduardo Sontag (1995) that the reachability problem of piecewise linear systems is undecidable. What is not known is for which subclasses of hybrid systems the reachability problem is decidable. What is lacking for control of hybrid systems is an understanding of what causes this undecidability. A fundamental study of this issue has been carried out by the CWI team since the mid 1990's with several publications on reachability. As part of this study, there has arisen the problem of the domain of attraction of exit sets of an affine system on a polytope. To make the problem tractable, attention was limited to such systems in the plane. A complete characterization of the domains of attractions of the respective exit sets was obtained. The results of the investigation are such that extension of the results to higher-dimensional systems is not so relevant, and in any way difficult because the results obtained depend on the use of planar geometry in substantial ways. The results of the investigation have important consequences for control synthesis, specific properties of the closed-loop system are best avoided because they have negative consequences for control. The computational properties of reachability are not the primary concern of the investigation but the computational properties trivially follow from the results obtained.

The publication of a paper on the control-to-facet problem for affine systems on polytopes was completed by L. Habets and J. van Schuppen [HvS04a].

3.6 Compact trajectory spaces

An approach to reachability and other properties by considering the entire trajectory space has been investigated in [Col04]. The subclass of hybrid systems considered is that of differential inclusions with discrete resets, which includes nonlinear hybrid systems. The key property is compactness of the trajectory space; this property allows the construction of probabilistic and symbolic descriptions of the system. Further, systems with compact trajectory space either display Zeno behavior, or have trajectories that have a lifetime extending to time infinity. The upper-semicontinuity of the underlying differential inclusion and reset map is a sufficient condition for compactness of the trajectory space.

3.7 Timed automata

We continue to work on controller synthesis for timed automata in order to solve problems of scheduling under different types of uncertainty. A paper summarizing our approach will appear in a journal version [AAM]. Another development of a more theoretical interest was the identification of the class of *recognizable* timed languages and the proof of its equivalence with deterministic timed automata [MP]. This can be seen as a sort of realization theory for timed discrete event systems.

3.8 Code Generation

In [CCM$^+$03] an automatic procedure for generating operational C code from Simulink models, via the synchronous data-flow Lustre, has been developed. This work has been applied to an automotive case-study of car steering assistant by Audi. Current effort is now directed toward code generation for mixed Simulink and Stateflow models, where the experience in the semantic problems of hybrid automata is very useful.

4 D-AA-2: Automotive Application

In Section D-CH-2, we have already reported the description of research activities regarding *observer design for hybrid systems* and *stabilization of linear discrete–time hybrid automata*. These results on hybrid controller synthesis had been originally motivated by engine control problems and successfully applied to address the specific motivating applications. Then, they had been significantly extended to consider more general contexts. In this section, we review in details the research activities closely related to automotive applications.

4.1 Idle Speed Control

A relevant research activity has been devoted to the synthesis of engine control algorithms for idle speed control, which was the first automotive case study proposed in this work-package. In [BBV$^+$02] and [BZVSV02], the idle speed control problem was formalized as a "safety" specification: given the hybrid model of a 4–cylinder port-injection engine, find a hybrid feedback controller that keeps the evolution of the crankshaft speed within a given range, against the action of unpredictable external continuous and discrete disturbances (namely, clutch switching and load torque). The hybrid models described in [BBV$^+$02] and [BZVSV02] are basically hybrid automata with both continuous and discrete control inputs (throttle valve position and spark ignition), where the latter is a little more detailed since it contains some nonlinearities (abstracted away in the former), and a more detailed description of clutch switching and torque generation.

Three different methodologies had been applied to design idle speed controllers:

- *A reachability-based approach.* We applied a reachability-based approach to solve the idle speed control problem proposed in [BBV$^+$02]. Details are reported in [Dan03]. The continuous and switching control laws of the idle speed safety controller can be derived from the corresponding maximal invariant set. However, due to nonlinearities in the hybrid model, it is hard, both theoretically and practically, to compute this set. For effective computation purposes, we restrict the continuous law of the throttle angle to be a piecewise constant function, whose value is changed synchronously with dead–center events. Since the model has a block-triangular structure, we apply the compositional assume-guarantee reasoning from model-checking to this controller design process. More concretely, by assuming that the speed stays in the desired range, one can estimate the duration of each stroke, which is used to determine the generated torque that can guarantee that the speed does not go out of the desired interval during the cycle. Then, based on the required torque, we determine the manifold pressure and the throttle angle accordingly. The problem of quantifying the performance loss due to the use of piecewise constant controls, in this specific engine control problem as well as in a more general context, had been investigated. In addition, some preliminary results had been obtained using a revised version of Verishift, as described in Section D-TL-2.

- *A control-to-facet approach.* A design methodology, based on the CWI team's research on the control-to-facet-problem for affine systems on polytopes, had been applied to the idle speed control problem (see [BDSVvS04] for a detailed report). The control objective is to keep the crankshaft speed within a specified interval, even in the presence of bounded disturbances. Applying a back stepping approach, it is possible to define a procedure to compute the inputs for the throttle valve and the spark ignition to achieve this control objective. First, the hybrid model described in [BBV$^+$02] was represented as an affine hybrid system on polytopes. The abstraction of the cylinder leads to a dynamic system with delays, the duration of the delays being dependent on the dynamics and on the input signal. Then, dynamical system properties, such as the existence of equilibrium states and the existence of periodic solutions, had been investigated. Due to the system being a series connection of positive affine systems on polytopes, explicit results could be obtained. The controller synthesis had overcome the following problems: (1) control with state space constraints for a system with delays; and (2) guaranteeing that the idle speed is maintained in the interval even in the case of disturbances. The approach is partly theoretical, with derivations of inequalities for states and inputs, and partly computational, with computations for states and inputs.

- *A command governor for GDI engines.* Finally, the design of an idle speed controller for gasoline direct injection (GDI) engines was considered. In GDI engines crankshaft speed regulation is achieved by acting on throttle valve and fuel injection. The idle speed control problem was formulated as a fuel consumption minimization problem, subject to constraints on engine speed and air-to-fuel ratio. In [ABC$^+$03a] a hybrid model for a GDI engine operating in stratified mode was proposed and a sub-optimal, but effective and easily implementable solution was obtained by resorting to the *Command Governor* methodology. In a command governor scheme, both input and state constraints are handled by a suitable modulation of the reference input (i.e. the engine speed and the air-to-fuel ratio in our case). Then, in [ABC$^+$03b] the approach was refined, by using robust techniques for a discrete-time relaxation of the hybrid model, which describes the multirate nature of the engine input signals. The obtained feedback controller is *correct by design*, in the sense that it ensures constraint satisfaction for the hybrid model of the GDI engine, in the presence of model uncertainties. This result is of particular interest in automotive applications where usually controllers are designed for continuous–time mean–value models and the specifications are not formally guaranteed.

4.2 Supervisory control of an automotive robotized gearbox

In collaboration with the Control Division of Centro Ricerche Fiat, Orbassano, TO, Italy, we designed a supervisory controller for the integrated management of the power-train, with the objective of optimizing comfort/ergonomic specifications and fuel consumption (see [BBM03a]). We designed a HYSDEL hybrid model of the system, capturing the switching dynamic behavior of the vehicle as a function of the selected gear, and a controller based on hybrid model predictive control techniques. We demonstrated that a good closed loop performance can be achieved through simulations on standard speed patterns. The synthesized control law can be implemented on automotive hardware as a piecewise affine function of the measured and estimated quantities.

4.3 Design Methodologies for Automotive Embedded Controllers

Hybrid system techniques had also been applied in the context of design methodologies for real–time embedded controllers. The design of automotive control systems is becoming increasingly complex as the level of performance required by car manufactures grows continuously and the constraints on cost and development time imposed by the market become tighter. A successful design, without costly and time consuming re-design cycles, can be achieved only by using an efficient design methodology that allows for component re-use and evaluation of platform requirements at the early stages of the design flow. In [BDF$^+$04], we illustrate the application of an integrated control-implementation design methodology to the development of the top three layers of abstraction in the design flow of an engine control system for motorcycles. The proposed design methodology is based on the principles of *platform-based design*. A platform, in this context, is a layer of abstraction that hides the unnecessary details of the underlying implementation and yet carries enough information about the layers below to prevent design iterations. Hybrid system techniques are extensively used to evaluate the behavior of the system at each layer of abstraction, using either hybrid simulations or formal verification techniques, with hybrid models that conservatively represent the behavior of the embedded controller and its interaction with the plant and the environment at the specified level of abstraction.

5 D-PP-2: Power Production and Distribution

The PP package comprises three case studies. PP1 and PP2 were proposed by EdF, whereas PP3 was supplied by ABB. During the past year most activities focused on PP3.

5.1 PP1: Steam Generator Water Level Control Problem

The goal of this case study is to use hybrid methodology to synthesize a reliable controller that keeps the water level in the steam generator of a nuclear power plant at a constant value, despite load variations and uncertainties in the sensor measurements. The group at Grenoble worked on this case study leading to the MSx thesis [Don03]. The approach was to first approximate the dynamics of the system by a piecewise affine model which can be determined from the given two "significant" linear dynamics (at high and low reactor load). This made it possible to approximate the nonlinear dynamics as closely as needed, while keeping the model simple enough to be studied with classical hybrid techniques. In a second step, the problem of specifying and verifying the stabilization properties of a given controller for this model was formalized, and the case where the controller is a PI controller with coefficients that depend on the operating point was studied.

The main achievement was the development of an algorithm that can check very quickly whether or not such a controller satisfies the given specifications. Exploiting the characteristics of the dynamics, the control specifications need to be checked only for a limited number of trajectories in order to determine if the specifications are satisfied along all possible trajectories.

Furthermore, this approach has been extended to sensor fault detection, which is based on an adaptation of Luenberger observers for our piecewise affine model.

5.2 PP2: Fossil Power Plant

The case study was presented in June 2003. In November, however, the project partners decided to cancel the case study due to reasons described in D-MG-2.

5.3 PP3: Electrical Power Systems

An electrical power system consists of numerous components connected together to form a large, complex system generating, transmitting and distributing electrical power. Electric power systems and additional preventive control schemes are designed in such a way, that the system should be able to withstand any single contingency, that is, outage of any single component without loss of stability and with all system variables kept within predefined ranges. Not all possible disturbances, however, can be foreseen at the planning stage and these may result in instability leading eventually to collapse or islanding of the system. Furthermore, because of environmental constraints on the extension of the transmission capacity, increased electricity consumption and new economic constraints imposed by the liberalized power market, power systems are operated closer and closer to their stability limits.

Under heavy load conditions, a power system can become unstable exhibiting slow voltage drops, that may lead to a voltage collapse resulting in a black-out if appropriate countermeasures are not taken. Several such voltage instability incidents have occurred around the world. As a consequence, voltage stability has become a major concern in power system planning and operation and the need for emergency control schemes that ensure stability - also during cascaded or multiple outages - has increased.

In 2001, ABB defined a case study [Lar03a] to let the project partners derive, test and compare such new control schemes. This case study, to which we refer as the 'full case study', comprises a four-bus power system, and has been mainly studied by ETH Zurich. In addition, ABB has also posed a simpler 'prelude' test case [Lar03b], which we call 'simplified case study', with two buses. The latter is primarily intended to get acquainted with the internal mechanisms of the more complex full case study. This case study has been studied by the two groups at Grenoble and at Lund. A separate group (outside of the CC project) at IBM Haifa has also recently initiated studies on this case study.

Both case studies are hybrid systems that incorporate not only discrete manipulated variables but also discrete events like logic and finite state machines. Furthermore, following a fault, both case studies are open-loop unstable leading to a voltage collapse if no appropriate countermeasures are taken by an emergency control scheme.

The case studies provide a much simplified representation of an actual power system, where a single load and a single transformer equivalent are used to capture the dynamic behavior of what is in reality a very complex system consisting of many power lines, transformers and loads. Early work [LRB02, LRB03] on stability assessment based on such equivalent models has shown that they can quite accurately capture the dynamics of complex power systems. Also, during the final year of the project, a case study of a more realistic scale will be developed and studied by the project partners.

Throughout the year, ABB has actively supported the groups at Grenoble, Lund and ETH Zurich in their efforts to apply their control schemes to the two case studies.

In the following, we give an overview of the solution approaches to the two case studies.

5.3.1 Full ABB Case Study

The solution of the full case study [Lar03a] utilizes a Mixed Logical Dynamical (MLD) system description and online optimisation (Model Predictive Control) using mixed-integer linear programming (MILP). More specifically, the power system was modeled as an MLD system by approximating the nonlinearities with PWA functions. This operation introduced only small modeling errors hardly noticeable in the control simulations thus proving the usefulness of the MLD modeling approach. It was shown that the load voltage can be stabilized by an appropriately tuned MPC controller using only nominal control moves. The tuning of the controller is straightforward and systematic allowing the designer to easily distinguish between nominal and emergency control moves. The results are summarized in [GML03].

5.3.2 Simplified ABB Case Study

For the simplified case study, the following has been achieved by the group at Grenoble (LAG):

Lyapunov-Based Hybrid Control [ACdWA03]. A Lyapunov-based hybrid control strategy for voltage stabilization of power systems was proposed. The algorithm utilizes a numerical search to decrease the value of an associated Lyapunov function subject to a set of constraints taking into account priorities in the use of the available actuator set. This led to a Lyapunov-based logic switching strategy that has been successfully tested on the simplified ABB case study.

Nonlinear Predictive Control [AACdW04]. A nonlinear predictive controller has been proposed to solve the simplified ABB test problem. The proposed control law should be easily generalizable to the original problem. It was shown that the risk-level related use of the different control actions is suitably handled leading to a voltage recovery that smartly uses the available possibilities leaving the load shedding as a last resort. Many validating scenarios have been studied to illustrate the effectiveness of the proposed approach.

5.3.3 Derivation of Simple Dynamical Models

The derivation of simple dynamical models is often a crucial step for the successful solution of control engineering challenges. The first year of efforts on the voltage stability benchmark at Lund have therefore been devoted to the derivation of a simplified dynamical model for controller design. The efforts have been pursued in close cooperation with the ABB partner and have been focused on the simplified case study which can be simplified to a nonlinear model with just two dynamical states.

The model includes a generator, a transmission line, a transformer with an on-line tap changer and a load. An important reason for voltage instability is that the load dynamically changes its impedance in order maintain a constant power consumption. This behavior can be modeled by a differential equation with the load impedance as the state. A second differential equation is used to describe the dynamics in the transformer, where the tap changer tries to regulate the voltage.

This model is able to capture two instability scenarios. In the first case, the system simply does not have the capacity to deliver the requested power. In this case, the model has no equilibrium points. A second instability scenario occurs, when in spite of an existing stable equilibrium point the system ends up in instability due to transients. In this case, the model has one stable and one unstable equilibrium.

5.3.4 Medium-Scale Case Study

According to the project plans, and because the full and the simplified case studies have been more or less explored and solved by the project partners, the development of a larger-scale case study has been started. A draft version of a medium-scale case study has been delivered to the groups at ETH Zurich and Grenoble for feedback so that a final version can be posed in early 2004.

6 D-TL-2: Tools

The following tool development activities took place in the second year:

6.1 Multi-Parametric Toolbox (MPT)

The aim of the Multi-Parametric Toolbox [KGBM03] is to provide efficient computational means to obtain optimal and sub-optimal feedback controllers for constrained linear and piecewise affine systems in a MATLAB programming environment. The toolbox offers a broad spectrum of algorithms compiled in a user friendly and accessible format: starting from different performance objectives (linear, quadratic, minimum time) to the handling of systems with persistent disturbances and additive and polytopic uncertainties. The algorithms included in the toolbox are a collection of results from recent publications in the field of constrained optimal control of linear and piecewise affine systems [BBM00, BBBM03c, GBTM03, GKBM03, GLPM03, GM03]. The toolbox can also be used to solve a broad class of problems which arise in the field of polytope manipulation: convex hulls, convex unions and envelopes, Minkowski sums, Pontryagin differences, as well as many other operations can be performed efficiently by MPT. Most of the functionality supports both single polytopes as well as non-convex unions thereof. Powerful analysis and visualization functions are also included. The toolbox is based on a object-oriented programming framework and utilizes state-of-the art optimization software (compatibility with CPLEX, NAG, CDD, SeDuMi and more). The toolbox is continuously updated to include new features. All researchers are invited to participate in the development.

MPT is publicly available from `http://control.ee.ethz.ch/~hybrid/mpt/`.

6.2 New developments in d/dt

The tool **d/dt** has been augmented with the following new functionalities:

- Verification of hybrid systems with both *continuous-time* and *discrete-time* components: this functionality has been applied successfully to an example coming from the domain of circuit design, namely verification of a Sigma-Delta modulator, a key ingredient in modern analog-to-digital converters.

- Reachability analysis of hybrid systems with nonlinear dynamics using simplicial decomposition and interpolation. This is an implementation of the results in [ADG03].

- Reachability analysis of differential algebraic equations using projection methods from geometric integration [DDM04]: this functionality has been used to verify several nonlinear analog circuits.

- Reachability analysis of uncertain bilinear control systems: this functionality allows to perform reachability analysis of uncertain bilinear systems with both multiplicative and additive control input:

$$\dot{x}(t) = Ax(t) + \sum_{j=1}^{l} u_j(t)B_jx(t) + Cu(t)$$

  where the input u is bounded (see [AD03]).

- Abstraction by projection: this functionality is used to reduce the dimension of a nonlinear continuous system by projecting away some continuous variables and producing a hybrid system with differential inclusion which is an over-approximation of the original continuous system (see [AD03]).

6.3 Additional work

1. Further debugging and testing has been carried on a revised version of Verishift, to assess the quality of the modified algorithm described in [CBB+03].

2. The architecture of a new package for hybrid reachability analysis has been designed at Parades to support the implementation of a new generation of algorithms, allowing for different computational methods and network architectures.

7 D-DS-2: Dissemination

7.1 Web Site

An important dissemination channel for the project is the web page which puts all available information in the public domain for the profit of the consortium members and the whole scientific community. It includes case-study description, tools, publications and information on project meetings as well as review-related material (including this report).

7.2 Major Hybrid Events

Members of the consortium are also very active in the organization and program committees of hybrid system events such as workshops and special sessions in large control conferences. The major dissemination activity for 2003 was the workshop *Hybrid Systems: Computation and Control (HSCC)* in Prague which was partially sponsored by the project. Additional copies of the proceeding were purchased and are being sent to potential clients of hybrid technology. Currently two project members are in the steering committee of the workshop, six participated in the program committee for 2004 (Philadelphia) and six papers describing work done within the CC project were among the 43 accepted this year (out of 120 submissions). Other hybrid events such as the IFAC ADHS03 workshop or the hybrid session in conferences such as CDC served as additional dissemination channels for the project results.

7.3 Dissemination toward other Projects

The hybrid system vision developed, among others, by the CC consortium, is now gaining momentum as an unavoidable ingredient of the design methodology of complex embedded systems. As one indication for this trend we mention the participation of Verimag in the submission of of the PROSYV project and the ESPACE integrated project for embedded systems in avionics. The consortia for these projects, who until recently focused only on verification of control programs without modeling their physical environment, realized that the next step for integrating formal methods in the design cycle is to move to hybrid verification techniques. Although these projects were finally not accepted, we believe that the world of embedded systems is now more open for hybrid systems ideas. Another indication for the increasing popularity of hybrid systems research in the control community is the participation of members of the consortium (ETH, Siena, Parades, Lund) in the preparation of the HyCon network of excellence in control, where hybrid systems occupy a central place. Other projects with which the CC project interacts include Hybridge, Ametist and the Artist network.

7.4 Dissemination toward Industry

The dissemination toward industry through the Parades-Magneti Marelli channel continued this year, including the following activities:

- The methodology for integrated control-implementation design of embedded systems, based on hybrid system modeling and verification techniques and reported in [BDF+04], had been presented in Magneti Marelli Powertrain (Bologna, Italy) during a one–day meeting with control engineers on May 12, 2003. After this meeting, the functional behavior of an entire engine control unit for a motorcycle application was described using the proposed hybrid system methodology by teams of 4-6 control engineers and Parades researches, in a sequence of nine full–day meetings held in Magneti Marelli Powertrain from mid May to the end of June, 2003.

- The use of hybrid system modeling techniques for the description of the functional and timing specification of embedded software implementing engine control algorithms had been investigated. In a sequence of five full–day meetings held in Magneti Marelli Powertrain in 2003, the semantics of tools used in automotive industry for control algorithm modeling and software automatic coding has been analyzed to evaluate their capability to capture the required hybrid formalism.
- Parades actively participated to the 7th "Antonio Ruberti" CIRA school for PhD students in control theory held in Bertinoro, Italy, 17–19 June 2003, and dedicated to the topic "Analysis and control of hybrid systems". The following two lectures had been given: "Embedded systems, platforms and design methodologies", by Alberto Sangiovanni-Vincentelli, and "Hybrid observers", by Andrea Balluchi.

7.5 Analog Verification

Another interesting development with industrial impact is the growing interest in hybrid verification techniques among designers of analog circuits. This is a very interesting development if we remember that discrete verification had its first success story in the hardware domain and the mixed digital-analog circuits are nothing but hybrid systems whose correct functioning is of a tremendous importance for embedded systems. We have done some encouraging experiments in applying the hybrid technology to such circuits and expect to continue the efforts this year as well, some of it in the framework of the new IST project PROSYD with the participation of IBM and STM.

7.6 Additional Dissemination Activities

- J.H. van Schuppen gave a lecture on *Introduction to the research topic of hybrid systems* during the *ERNSI Workshop System Identification*, Noordwijkerhout, The Netherlands, 6-8 October 2003.d
- O. Maler gave a one-day tutorial on *Timed automata and the state-space based approach to planning and scheduling* in the ICAPS (AI planning and scheduling) workshop in Trento, June 2003.
- A curriculum for common background for control and software engineers was developed by P. Caspi and taught experimentally to computer science students in Grenoble.
- Two workshops previously organized by Anders Rantzer have been documented in books published by Springer this year [RB03, JR03].
- A one-day workshop *Hybrid Systems: Modeling, Control Design and Applications* was organized by M. Morai in the American Control Conference with the participation (among others) of F. Borrelli (ETH) and E. Gallestey (ABB).
- M. Morari gave a plenary lecture entitled *Hybrid systems* at the European Control Conference. A. Rantzer gave a a semi-plenary talk on *Stabilization of nonlinear systems* in the same conference.
- A paper by O. Maler, *Control from computer science* was published in the Annual review of control [Mal02]. The papers summarizes hybrid systems research from a computer science perspective.

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